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**CURRENT HYPERSONIC AND SPACE VEHICLE FLIGHT
TEST AND INSTRUMENTATION**

John J. Spravka^{*} and Timothy R. Jorris[†]

**AIR FORCE TEST CENTER
EDWARDS AFB, CA**

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Current Hypersonic and Space Vehicle Flight Test and Instrumentation

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Abstract

Hypersonic flight test applies to suborbital, space transit, and space access vehicles. Recent programs are being initiated by the US Air Force, Defense Advanced Research Programs Agency (DARPA), NASA, and commercial companies. The USAF and DARPA are pursuing technologies to meet the objectives of the High Speed Strike Weapon program. DARPA is also looking for new ways to satisfy the goal of Operationally Responsive Space; a means of inserting a payload into orbit in hours instead of months at a cost of millions instead of hundreds of millions. One of the primary challenges to testing these systems will be collecting the data generated by these high speed vehicles.

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I. Introduction

The advancement of hypersonic technologies is designed to support the Conventional Prompt Global Strike [1] and the High-Speed Strike Weapon (HSSW) [6] programs being managed by the Air Force Research Lab (AFRL) and Defense Advanced Research Projects Agency (DARPA) [7]. While these advancements present challenges in vehicle design in aerodynamics, flight controls, structural loads, heating and propulsion, they also present a challenge to collecting the data generated by these high speed vehicles during flight.

The premise of this paper is to reacquaint the academic and flight test community with past data collection technologies and introduce them to future potential methods for collecting data on high speed, unmanned test vehicles. Past projects' data collection systems and future potential data collection systems are reviewed.

II. Previous Program Data Collection Systems

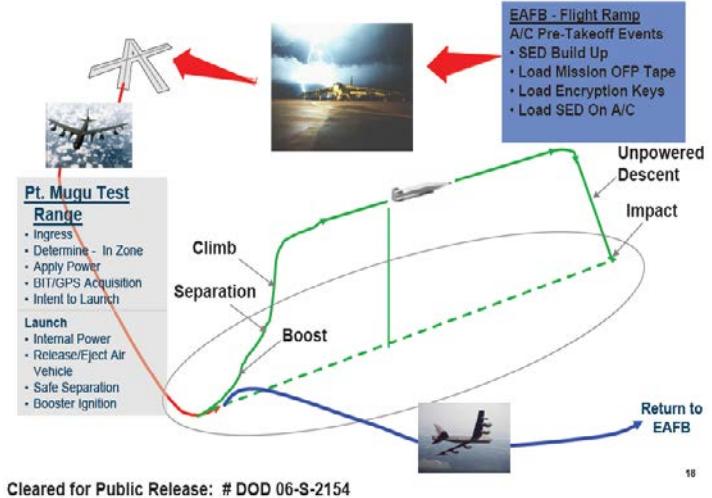
Conventional or legacy air vehicle data collections systems are well known and in use on numerous test aircraft programs such as F-35, F-22, B-2, and C-17. Sub- and Supersonic air vehicle instrumentation systems are typically able to transmit/receiver data at esdtablish MBS with a constrained bandwidth. Transmission/reception max range limits are typically on the order of hundreds to thousands of miles which can be extended through telemetry relay antennas. Past test programs that pushed the boundaries of air vehicle data collection technologies include AFRL X-51 Scramjet Engine Demonstrator and DARPA Hypersonic Technology Vehicle (HTV-2). TM data transmission/reception for these programs was very difficult and costly due to 1) the high speed at which the vehicles were traveling and 2) the extended ranges over which the vehicles flew over water.

A. X-51A Scramjet Engine Demonstrator

The X-51A was launched from a B-52 over the Point Mugu Sea Range. TM data were transmitted/received over an air vehicle powered and glide flight range of approximately 350 nm from the point of release from the B-52. The X-51A program utilized three different TM instrumentation platforms to collect data from the X-51A. Data was collected on the B-52 launch platform (Figure 1 below) both prior to and after X-51A release. Data were also collected by a ground stations at Vandenberg AFB and on San Nicholas Island within the Pt Mugu Sea Range. Data were also collected by a specially instrumented Navy P-3 aircraft stationed approximately 260 nm from the initial launch location at an altitude of approximately 20,000 ft. The transmit/receive range of the P-3 instrumentation suite was approximately 200 nm.



Figure 1 X-51A mounted under wing of B-52 at Edwards AFB



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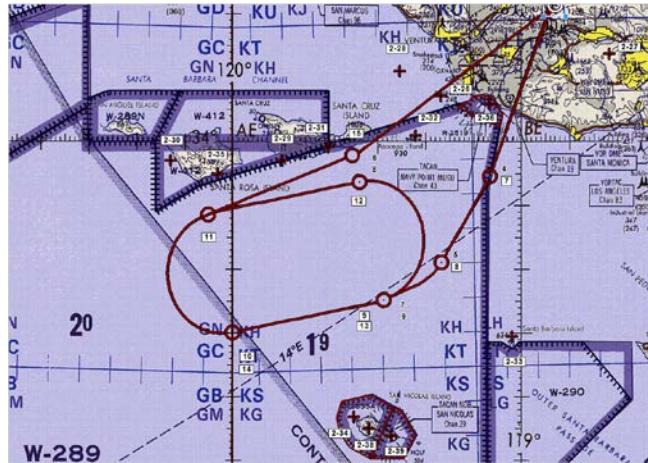


Figure 2 X-51A Launch profile over restricted water range

Valuable data were collected and relayed on all four powered flights by these TM assets. Flight one on 26 May 2010, had 200 seconds of scramjet burn accelerating to Mach 5 [10]. For the second flight on 13 June 2011, the scramjet lit successfully but failed to transition to full power [11]. For the third flight on 14 Aug 2012, the X-51A safely separated from the B-52 and the rocket booster fired as planned. However after 16 seconds, a fault was identified with one of the cruiser control fins. Once the X-51A separated from the rocket booster, approximately 15 seconds later, the cruiser was not able to maintain control due to the faulty control fin and was lost [12]. The fourth and final flight was a record-setting 210 seconds of scramjet combustion reaching a hypersonic speed of 5.1 Mach number [8]. On powered flight #4 the X-51A transmitted TM continuously from its release location from the B-52 to its eventual splash-down point in the Pacific Ocean.

B. Boost Glide Vehicles

A boost glide vehicle, for this paper, refers to an unpowered hypersonic vehicle that is launched from a ground based booster and then glides after separation. The Air Force flew the Hypersonic Technology Vehicle 2 (HTV-2) and the Army flew the Advanced Hypersonic Weapon (AHW). The two programs have similar challenges except their mission distances are significantly different. HTV-2 was launched from Vandenberg AFB with a planned flight to Kwajalein Atoll [13] approximately 3000 nm away, whereas AHW only flew from Kauai in Hawaii to Kwajalein Atoll [14], as seen in Figure 2.

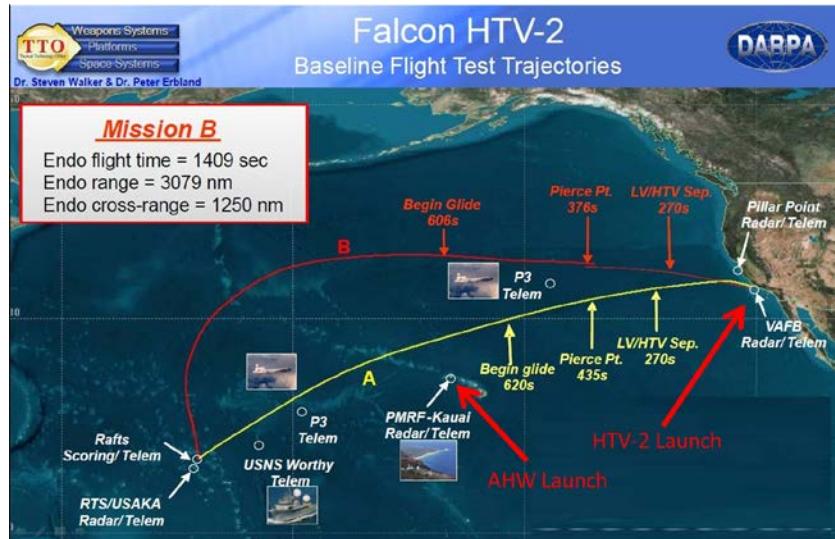


Figure 2 HTV-2 and AHW Launch Locations

i. Hypersonic Technology Vehicle 2 (HTV-2)

The depiction in Figure 3 shows the entire HTV-2 flight profile [15]. The vehicle was launched atop a Minotaur IV Lite from Vandenberg AFB, CA [16]. The first flight on 22 Apr 2010 collected 9 minutes of unique flight data but didn't complete its full mission. "The Engineering Review Board (ERB) concluded that the anomaly resulted from flight control authority limitations to operate at the angle of attack the vehicle was programmed to fly for the speed and altitude of the flight. Detailed analysis conducted by the ERB revealed that the most probable cause of the HTV-2 flight anomaly was higher-than-predicted yaw, which coupled into roll thus exceeding the available control capability at the time of the anomaly". [17]

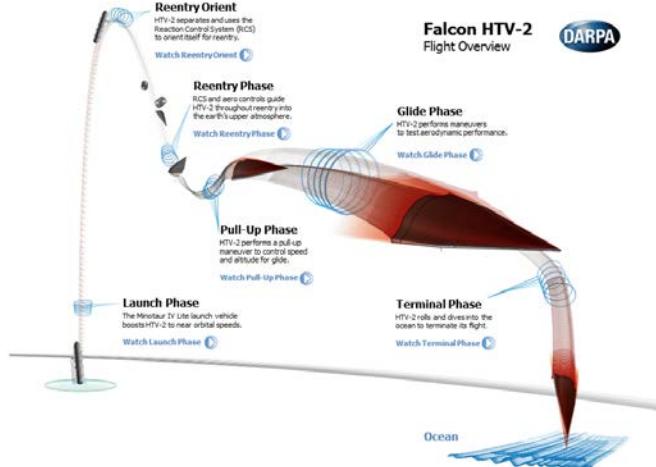


Figure 3 DARPA Falcon HTV-2 Flight Profile

The second flight on 11 August 2011 successfully demonstrated stable aerodynamically-controlled flight at speeds up to Mach 20 for nearly three minutes; however this flight also ended prematurely. “The ERB concluded that the ‘most probable cause of the HTV-2 Flight 2 premature flight termination was unexpected aeroshell degradation, creating multiple upsets of increasing severity that ultimately activated the Flight Safety System.’” [18]

The data collected for each of these flights was instrumental in being able to determine the causes of each vehicle failure during flight and will be extremely valuable in guiding the design of future hypersonic flight vehicles. Collecting the data to support each of these flights was again, a challenge due to both the speed of the vehicle and the distance traveled during its flight. In order to continuously collect that TM data throughout the vehicles flight trajectory it was necessary to assemble a “string of pearls” instrumentation assets over the course of the planned trajectory. This string of pearls consisted of land, sea and air based instrumentation platforms.

Specifically, the land assets, like the X-51A resources, consisted of Vandenberg and Pt Mugu Sea Range ground stations. The sea assets consisted of specially instrumented ships deployed to sea for a period of several days to weeks to allow for travel time to the pre-planned location and to accommodate any flight delays. The air instrumentation assets again included specially equipped P-3 aircraft. As one would expect, the cost of operating all of these assets for the period of time required was in the millions of dollars for just one flight.

ii. Army’s Advanced Hypersonic Weapon (AHW)

The flight of the AHW lasted less than 30 minutes on 17 November 2011. “The AHW is a first-of-its-kind glide vehicle, designed to fly within the earth's atmosphere at hypersonic speed and long range, was launched from the Pacific Missile Range Facility, Kauai, Hawaii, to the

Reagan Test Site, U.S. Army Kwajalein Atoll, Marshall Islands.” [14] Figure 2 shows the relationship between Vandenberg AFB, Kauai, and Kwajalein.

III. Future Data Collection Systems

A. DARPA Airborne Launch Assist Space Access (ALASA)

The goal of a project funded by DARPA called the Airborne Launch Assist Space Access (ALASA) program, started in late 2011, is to develop an air launch system that can place a 45-kilogram (100-pound) payload into orbit for less than \$1 million per mission [21]. Achieving that cost goal led DARPA to focus on what the real cost drivers of launch operations are. “If I’m going to hit a million-dollar-per-flight target, I’ve got to do things in such a fundamentally different way that I change the cost equation for all the stuff in a space launch that has nothing to do with the rocket,” said Mitchell Burnside Clapp, the DARPA ALASA program manager [21]. The Boeing ALASA concept intends to use F-15 aircraft that require no modifications. The rocket, for example, will use the same communications protocols as weapons systems typically mounted on that aircraft. “ALSA is not a weapon, but it does talk the same language as weapons speak,” Clapp said. “There are no software changes needed for the F-15. That is a huge advantage.” [21]



Since the ALASA payload will be deployed in low earth orbit (LEO) the payload launch platform instrumentation system will require a range equal to its eventual payload deployment altitude and cross range from the instrumentation relay and endpoint reception systems on the ground.

B. AFRL/DARPA Reusable Booster System Program

The Reusable Booster System (RBS) Pathfinder was “a promising approach to meet the Air Force’s future spacelift needs. The RBS consists of an autonomous, reusable, rocket-powered first stage with an expendable upper stage stack. The reusable first stage launches vertically and carries the expendable stack to the staging point. From the staging point, the reusable first stage returns directly to the launch base, landing aircraft-style on a runway.” [2] Figure 4 shows a graphic of the boost back concept.

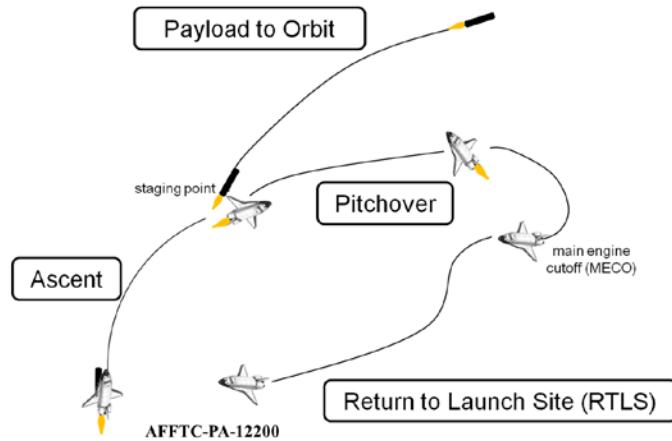


Figure 4 Reusable Booster System (RBS) Conceptual Profile

A potential test flight profile of the reusable first stage is shown below in Figure 9. TM data collection and relay assets will have to not only be capable of transmitting/receiving data over a long range horizontally but also vertically. This presents new challenges because air assets used on previous programs such as the P-3 has a service ceiling altitude of only 23,000 ft.

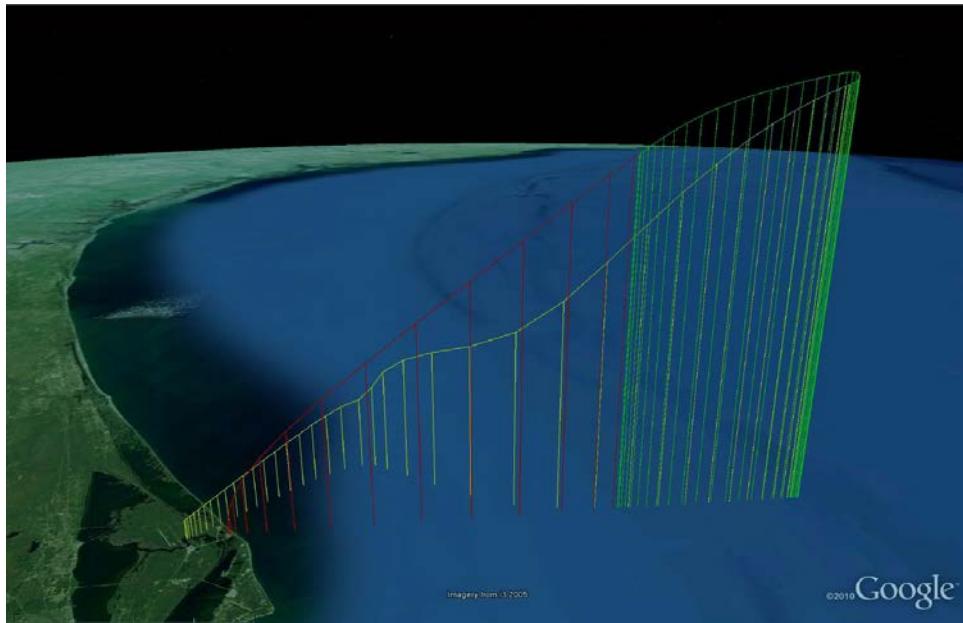


Figure 5 Reusable Boost System Example Trajectory

C. Experimental Spaceplane (XS-1)

The Experimental Spaceplane (XS-1) [5], solicited by DARPA, is aimed at developing a reusable first stage to deploy a 3K – 5k lb payload to orbit for under \$5M per launch. Take-off and landing can be horizontal, vertical or a combination of both. An artist concept is shown in Figure 6. Again, the instrumentation transmit/receive assets would have to be capable to transceiving data over a very long range at low to high altitudes.

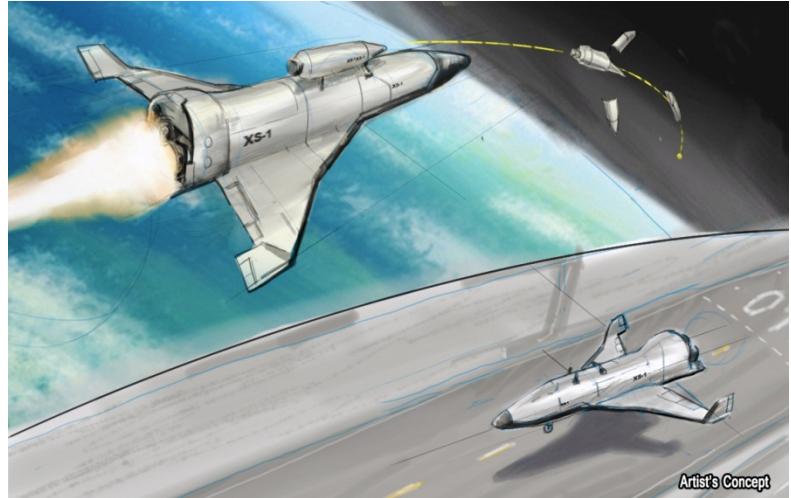


Figure 6 Artist Concept of Experimental Spaceplane (XS-1)

D. High Speed Strike Weapon System

AFRL and DARPA have teamed up to manage two different hypersonic propulsion technology development programs; Tactical Boost Glide (TBG) and Hypersonic Air-breathing Weapon Concept (HAWC). Both programs are designed to develop necessary technologies to achieve hypersonic or near-hypersonic speed in a cruise missile sized platform. AFRL is in the early stages of developing the required technologies to support these end products.

i. Tactical Boost Glide (TBG)

Boost glide vehicles achieve their high speed by being boosted by a high thrust rocket to high altitude and gliding back down to a lower altitude. TBG will have an intended range that is “tactical” and less than HTV-2. The Army’s Advanced Hypersonic Weapon (AHW) is a boost glide vehicle and flew 3,700 km on its first test flight [32]. Both HTV-2 and the AHW required a long line of aerial and ship-based TM collection and relay platforms to transmit the data back to the control room. This type of TM support is very expensive. Despite the TBG reduced flight range, testing in this flight regime will still require range assets that are able to support delivering TM data across long ranges and at high altitudes. Many present day and future programs are not funded to a level that would support repeating the “string of pearls” TM collection and relay system that supported HTV-2. In order to avoid this high cost new TM collection and relay systems have to be developed to provide the same level of performance at a much cheaper cost.

ii. Hypersonic Air-breathing Weapon Concept (HAWC)

Due to the long distance of the anticipated HAWC test flight profiles HAWC testing will also require range assets that are able to deliver TM data across long ranges while avoiding the cost of traditional “string of pearls” TM data collection and relay systems.

IV. Proposed TM Data Collection/Relay Technology Systems

A. Aircraft Platforms

A number of UAVs have already served as sensor data and TM relay platforms supporting a specific program or purpose. However, they have typically been single individual systems not a group of systems working together supporting one flight vehicle or program. In order to adequately support a hypersonic or space transit flight test program these UAVs would have to be able to stay aloft for potentially days at a time to support launch delays. There would have to be sufficient numbers of them to support the long distances traveled by hypersonic test vehicles. The instrumentation systems onboard those UAVs would have to have sufficient power to reach boost glide test vehicles at very high altitudes.

Another area of potential use for UAV TM platforms is air vehicle imaging. Obtaining infrared or electro-optical images of a hypersonic or space transit vehicle during flight can greatly enhance anomaly investigation and resolution. Vehicle heating can be observed and used to determine structure materials deterioration or failures during flight. The imagery can also be compared with existing models and updated so as to influence future designs. Atmospheric sensing is another capability that when paired with a UAV platform can

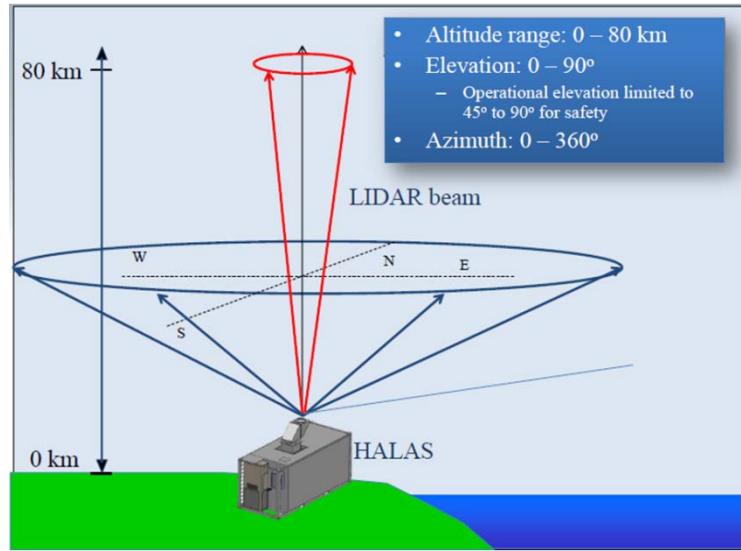
Potential UAV platforms that could support the above-described functions are Global Hawk, Predator, Lockheed Martin's Integrated Sensor in Structure Blimp. One program supportability issue would include the cost of sustaining these systems when not actually supporting test execution. These costs would include the proficiency training required of the UAV operators and maintaining and upgrading the UAV and ground station hardware and software.

B. Space-based Platforms

There are already in place several satellite based options to collecting and relaying TM data. One is the NASA Tracking and Data Relay System (TDRS). The initial setup cost can range anywhere from \$250K - \$1M [33]. However, once the operation configuration is set the system can support data collection/relay at a cost of only \$130 per minute. Other potential satellite networks that could possibly support the hypersonic and space transit flight test TM requirements are InmarSat [34], Iridium [35], Orbcomm [36], ViaSat [37] and Tactical Targeting Network Technology [38]. So while TDRS and similar networks of satellites are continually being updated with faster and larger bandwidth capability, existing and future capability must be assessed to determine if they will meet future hypersonic and space transit vehicle test requirements.

V. Additional Flight Test Instrumentation

The Office of the Secretary of Defense (OSD) High Speed Systems Test (HSST) program is developing atmospheric sensing technology that could replace weather balloons and chase aircraft; particularly since a hypersonic chase aircraft is currently not available. The High Altitude LIDAR Atmospheric Sensing (HALAS) system is a ground based, portable LIDAR system using an ultra-violet laser and scanner system to measure atmospheric conditions (density, temperature, pressure, wind speed/direction, O₂ content) along a vehicle's flight path at altitudes up to 80 km (250k feet). This will result in significantly more accurate flight test data and vehicle performance estimates with low uncertainties and better spatial and temporal resolution. The system also has the capability to provide near real-time and highly accurate measurements at lower altitudes to support range safety operations.



Based on predicted performance, the HALAS uncertainty is significantly better than traditional Rawinsonde balloon data. This comparison only considers the atmosphere in the near vicinity of the balloon, it does not take into account uncertainty improvements gained by multiple balloons or modelling. However, such balloon corrections traditionally do not result in an order of magnitude improvement, as demonstrated with the HALAS.

Altitude (kft)	Balloon Uncertainty	HALAS Uncertainty
20	0.47%	0.023%
30	0.49%	0.021%
40	0.63%	0.022%
50	0.71%	0.027%
60	1.01%	0.036%
70	1.30%	0.050%
80	1.87%	0.069%
90	2.86%	0.092%
100	4.57%	0.120%

VI. Conclusions

There are multiple hypersonic and space transit vehicle technology programs working to satisfy the Department of Defense and NASA objectives. Each is assaulting the challenges inherent in the hypersonic arena. One of these challenges is the collection and relay of vehicle TM data for real time and post flight data analysis. Recent programs, such as the X-51A and HTV-2 achieved these objectives at a high cost which cannot be overcome by future test programs. It is the role of the flight test community to explore and identify those TM data collection/relay technologies that can deliver the required performance to support numerous different types of test vehicles at a reasonable cost.

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[37] ViaSat - <https://www.viasat.com/broadband-satellite-networks/high-capacity-satellite-system>

- [38] Rockwell Collins Tactical Targeting Network Technology (TTNT) -
<http://rockwellcollins.com/~/media/Files/Unsecure/Products/Product%20Brochures/Communication%20and%20Networks/Networks/Tactical%20Targeting%20Network%20Technology/TTNT%20brochure.aspx>



412th Test Wing



War-Winning Capabilities ... On Time, On Cost



U.S. AIR FORCE



Current Hypersonic Flight Test Instrumentation Challenges

June 2015

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Integrity - Service - Excellence



Overview



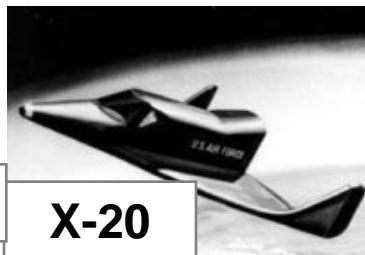
- Previous Data Collection Systems
- Future Program Requirements
- Future Data Collection Systems



Hypersonic CTF Lineage



X-15



X-20
Dynasoar



X-24A



X-24B

SPACE SHUTTLE

Manned Spacecraft Office (1959-1969)

- X-15, X-20 Dynasoar

Research Projects Branch (1970-1974)

- X-24A, X-24B Lifting Bodies

Office of Advanced Manned Vehicles (1975-1986)

- Space Shuttle, X-24C, BGV

Research Projects Office (1987-1995)

- X-30 National AeroSpace Plane

Access to Space Office – (1996 – 2003)

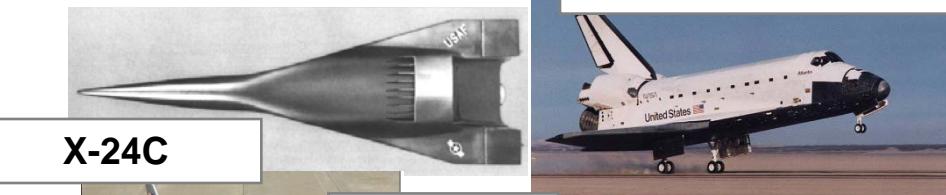
- X-33, X-34, X-38, X-40A

Hypersonic Flight Test Team – (2004 – 2007)

- X-43, X-37A

Hypersonic Combined Test Force – (2008 – present)

- X-37B, X-51A, HTV-2, Dream Chaser



X-24C

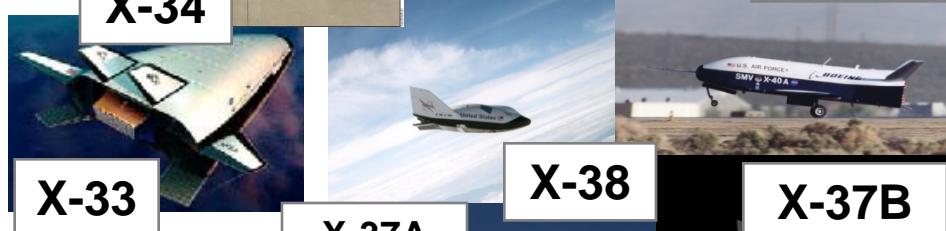


X-30 NASP



X-34

X-40A



X-33

X-38

X-37B

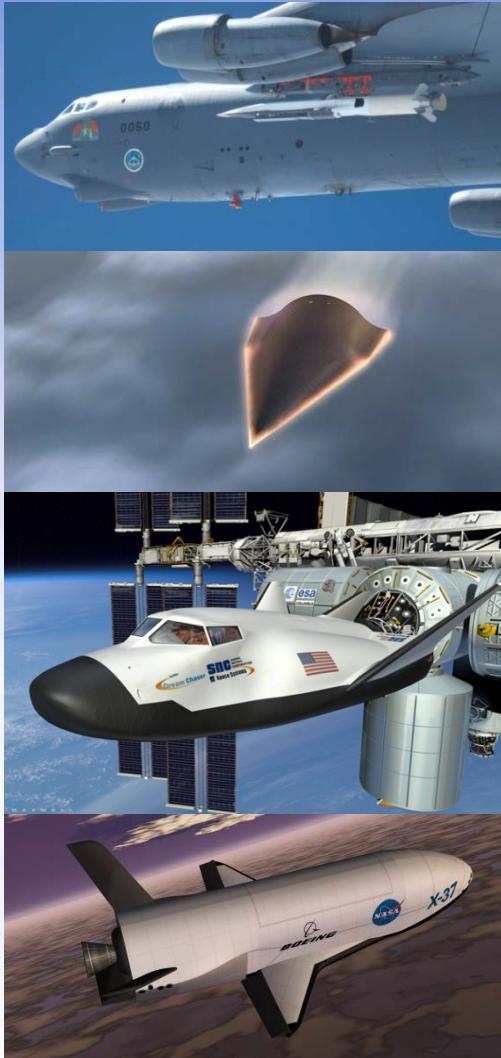


X-51

X-43A



Hypersonic CTF Programs



X-51A

AFRL/RQ, Boeing, Pratt-Whitney
High Speed Strike Weapon
AFRL/RW

HTV-2, Lockheed-Martin
Integrated Hypersonics

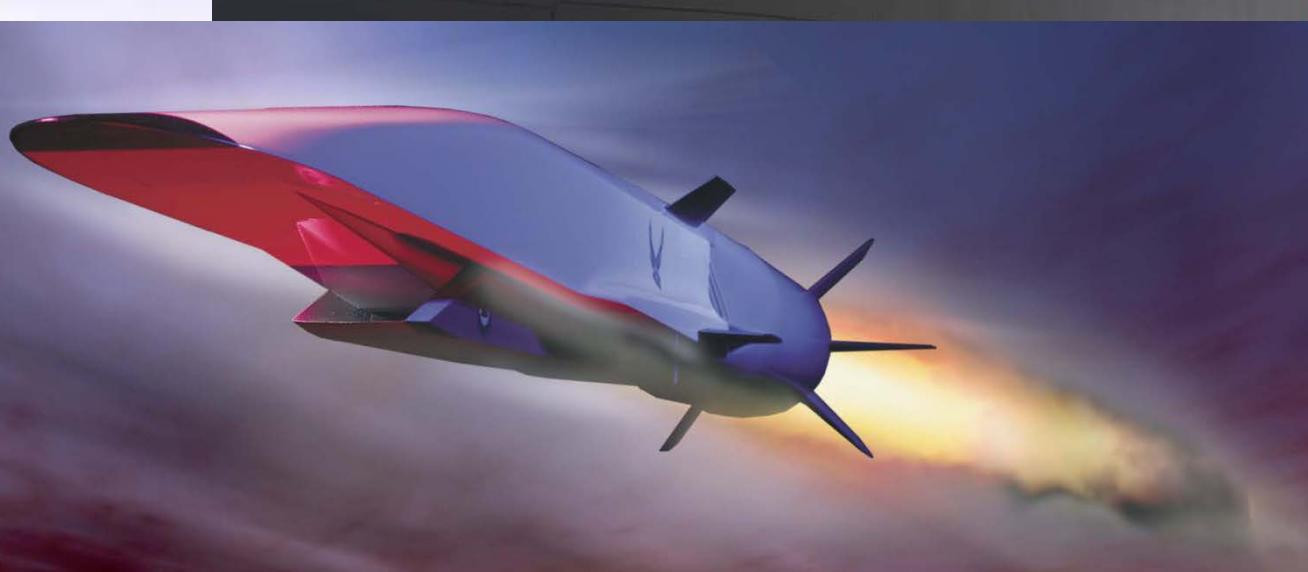
} DARPA

Dream Chaser: NASA Commercial Crew Dev
Sierra Nevada Corp, Dryden

X-37B – Orbital Test Vehicle
AF/RCO, Boeing



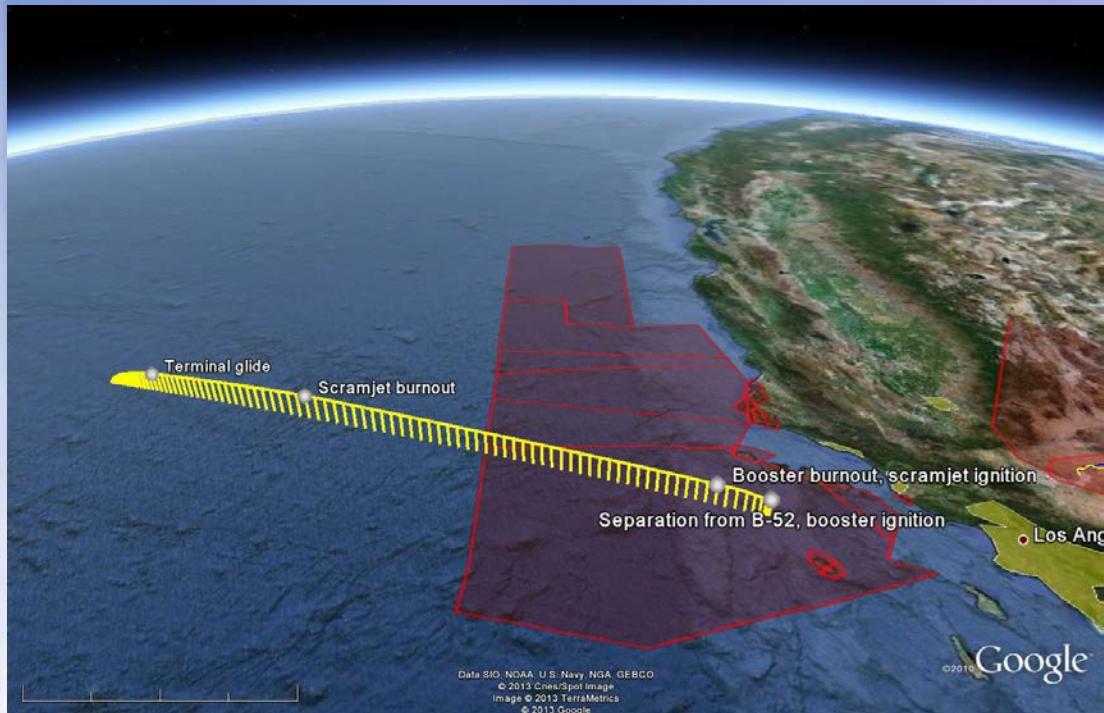
X-51A Scramjet Engine Demo



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X-51A: Pt Mugu Sea Test Range



Ranges: Pt. Mugu, Vandenberg

Launch point: B-52, 50 kft

Max Alt*: 71 kft MSL

Range: 310 nmi

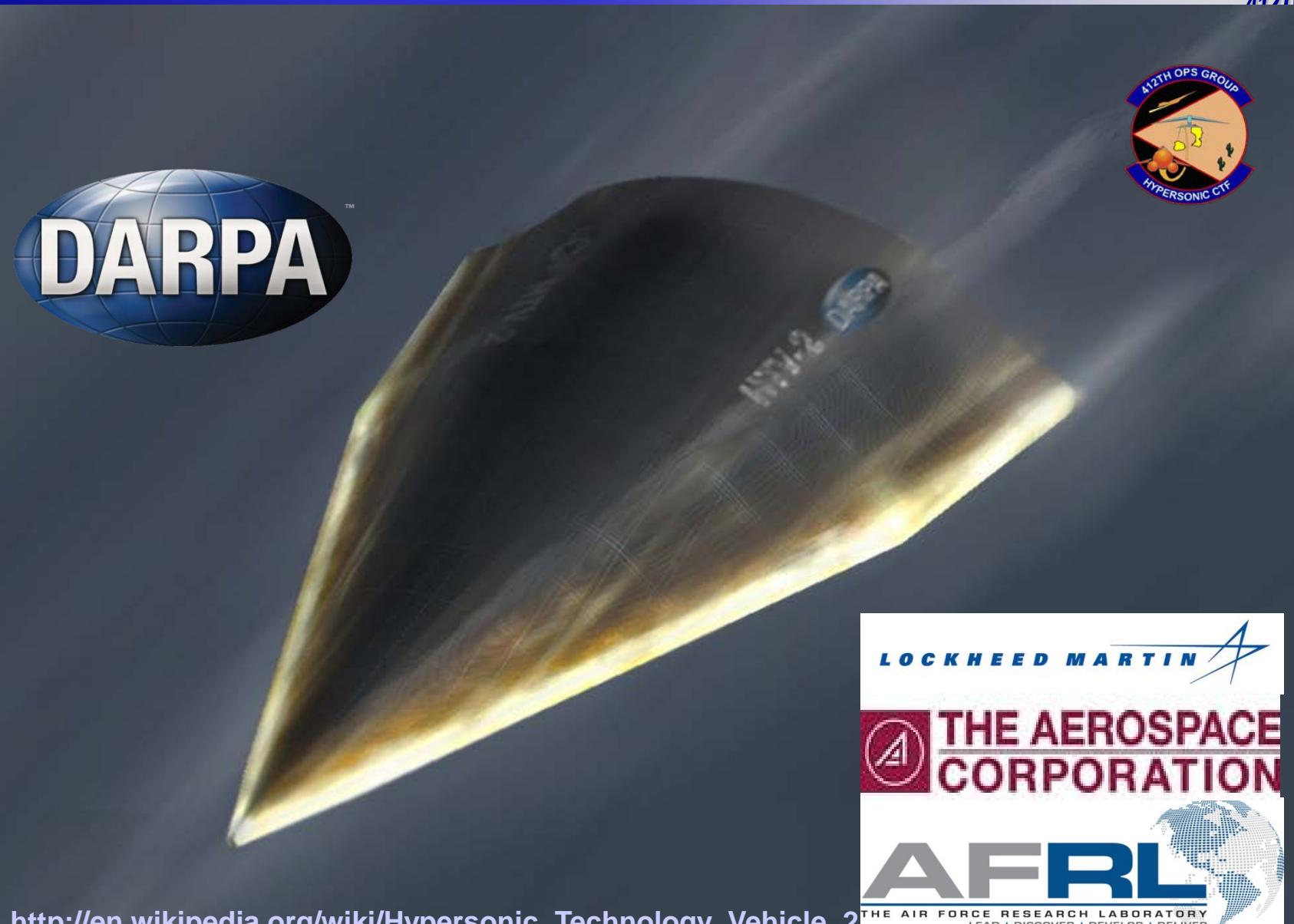
Sponsor: AFRL (Wright-Patt)





HTV-2

Hypersonic Technology Vehicle

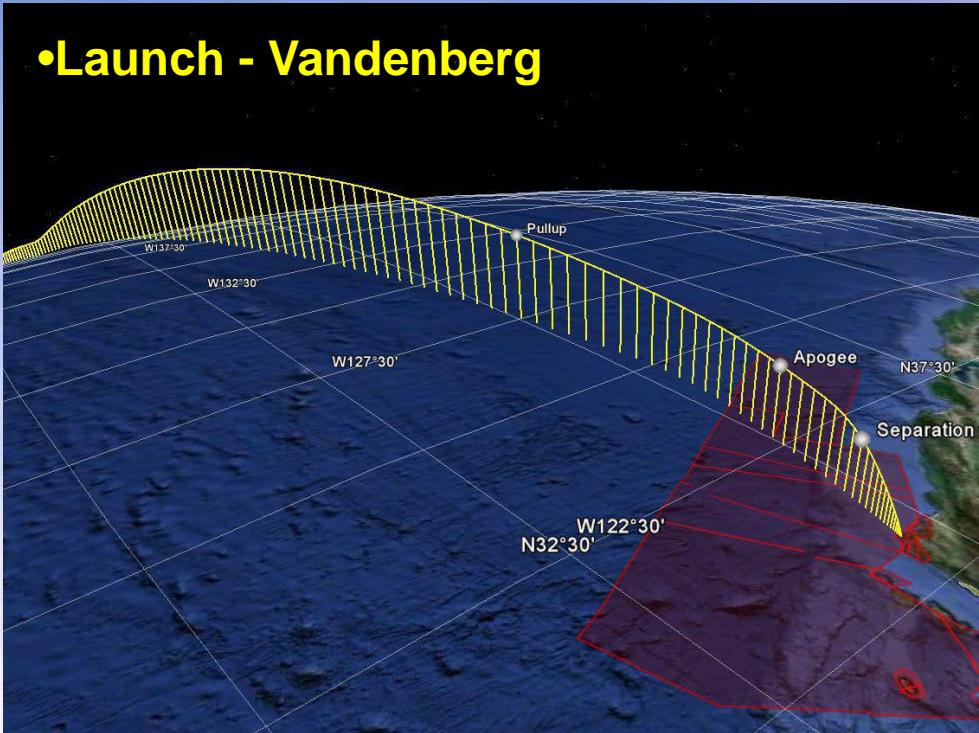




HTV-2 (Integrated Hypersonics)



- Launch - Vandenberg



Ranges/Launch: Vandenberg
Terminal: Kwajalein
Altitude at coast: 450 kft MSL
Range: 4000+ nmi
Sponsor: DARPA

- Mid - Avoids Hawaii



- Terminal - Kwajalein





HTV-2

Hypersonic Technology Vehicle



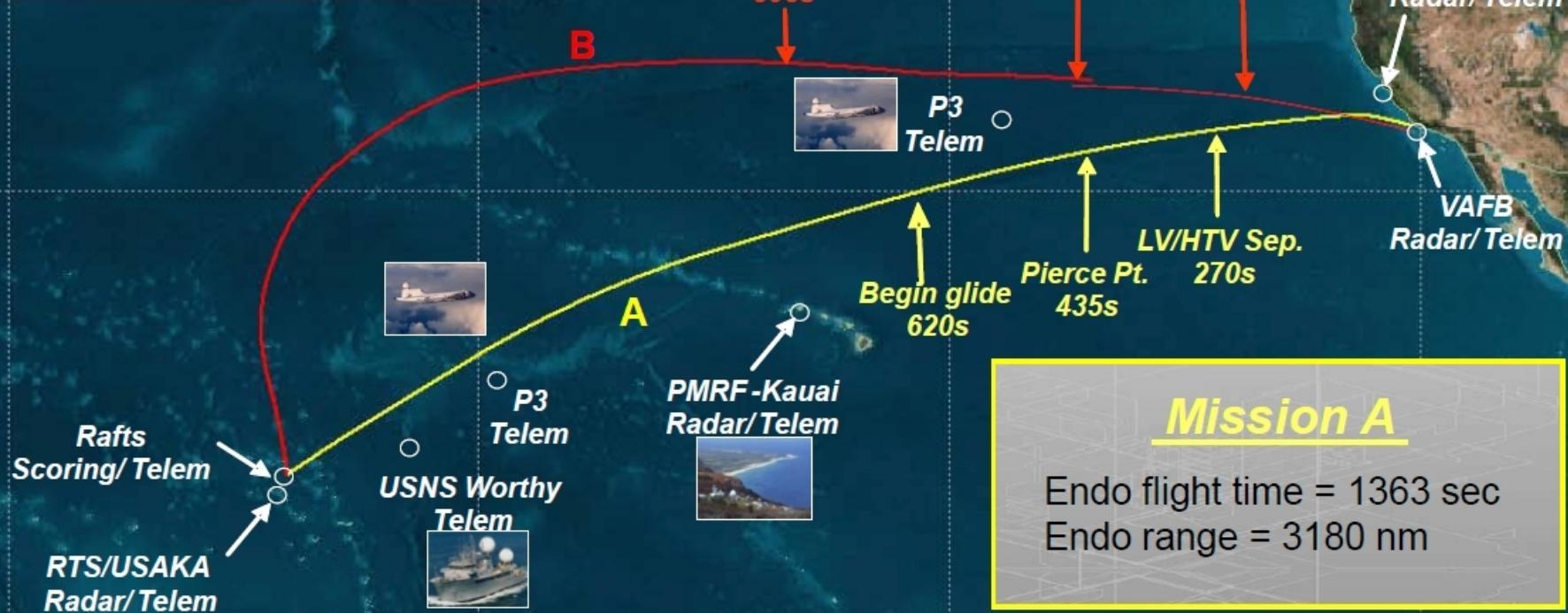
Dr. Steven Walker & Dr. Peter Erbland

Falcon HTV-2

Baseline Flight Test Trajectories

Mission B

Endo flight time = 1409 sec
 Endo range = 3079 nm
 Endo cross-range = 1250 nm





Future Program Requirements

412TW



Artist's Concept





Speed is the new stealth

412TW

Hypersonic missiles

Speed is the new stealth

Hypersonic weapons: Building vehicles that fly at five times the speed of sound is a tall order. It's been done only once, by the X-51. It's hard, but researchers are trying

The Economist

gly

Jun 1st 2013 | From the print edition





High Speed Strike Weapon

<http://www.lockheedmartin.com/us/products/high-speed-strike-weapon--hssw-.html>



“The technologies requiring early flight testing are included in a demonstration effort that will begin later in Fiscal Year 2013 called the **High Speed Strike Weapon (HSSW)**.”

“ ... compatibility with Air Force 5th generation platforms to include geometric and weight limits for **internal B-2 Spirit** bomber carriage and **external F-35 Lightning II** fighter carriage.”

“The flight demonstration will be the first **tactically-relevant** demonstration of **Mach 5.0 plus** airbreathing missile technology.



DARPA HAWC



Objective: Long range strike vs time critical or heavily defended targets.



Vehicle Performance:

Range: Greater than 300 nm

Altitude: Greater than 60K ft

Data Collection/Transmission requirement:
Range greater than vehicle performance range



DARPA TBG



Objective: Air launched
tactical boost glide
demonstration



Vehicle Performance:
Range: Approximately 500 nm

Data Collection/Transmission requirement:
Range greater than vehicle performance
range



Advanced Hypersonic Weapon

412TW



Sandia's Integrated Military Systems Program - AHW

Flight 1A: Nov. 17, 2011, Sandia's Kauai Test Facility to Kwajalein.

Flew almost 2,500 mi in less than 30 min.

Demonstrated viability of boost-glide approach to long-range atmospheric flight and data collection.

AHW was selected as a Lockheed Martin NOVA award winner.



DARPA ALASA



Objective:
**Deploy a 100 lb
payload to LEO**
**For less than \$1M
per mission**



Artist's Concept

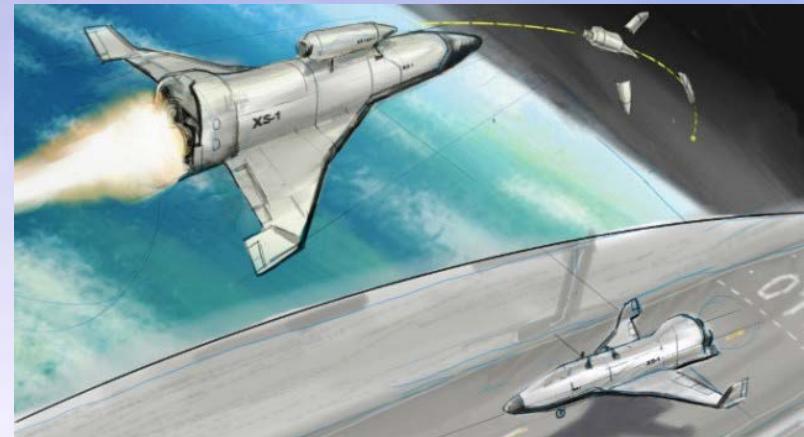
Instrumentation requirement:
**Range equal to payload deployment
altitude**



DARPA: XS-1



Objective:
Deploy 3K – 5k lb
payload to orbit for
under \$5M per launch



Data Collection/Transmission requirement:
Transceive data over very long range at low
to very high altitudes



Future Data Collection Systems



Ground Based



Aircraft Based



Space Based

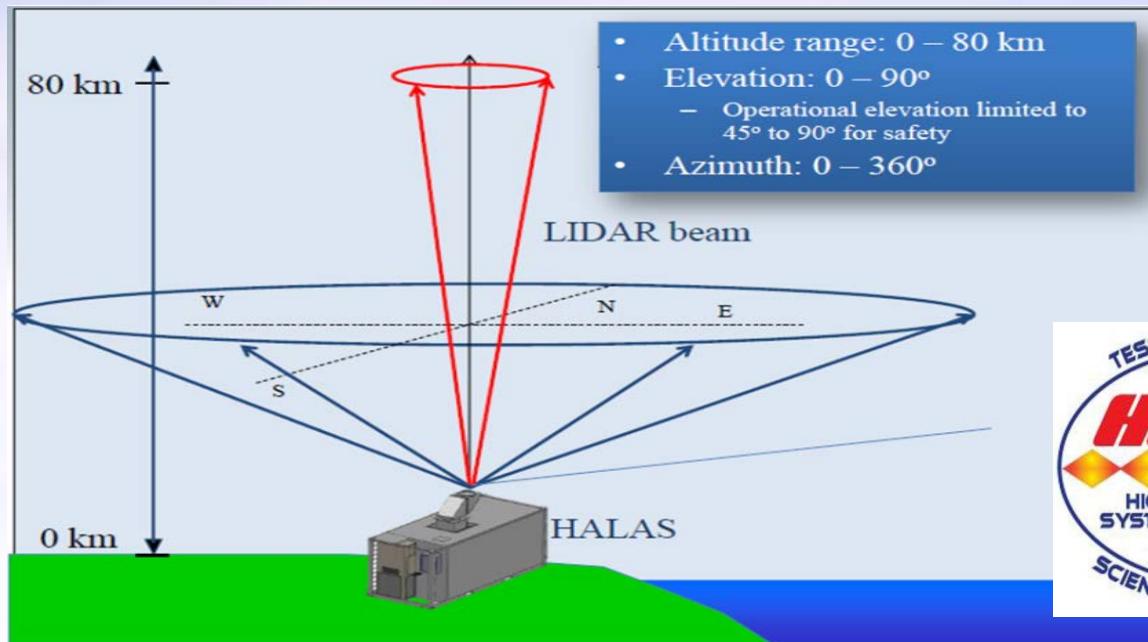




Ground Based

HALAS - High Altitude LIDAR Atmospheric Sensing

- Measures atmospheric density, temperature, pressure, wind speed/direction, O₂ content
- Ultra-violet laser and scanner; 80km ceiling
- Ground-based, portable; reduced uncertainty
- Replaces weather balloons and chase aircraft





Ground Based

412TW

HALAS - High Altitude LIDAR Atmospheric Sensing

- Predicted air density uncertainty values
- Actuals show balloon equivalence at lower altitudes but match predictions at higher altitudes

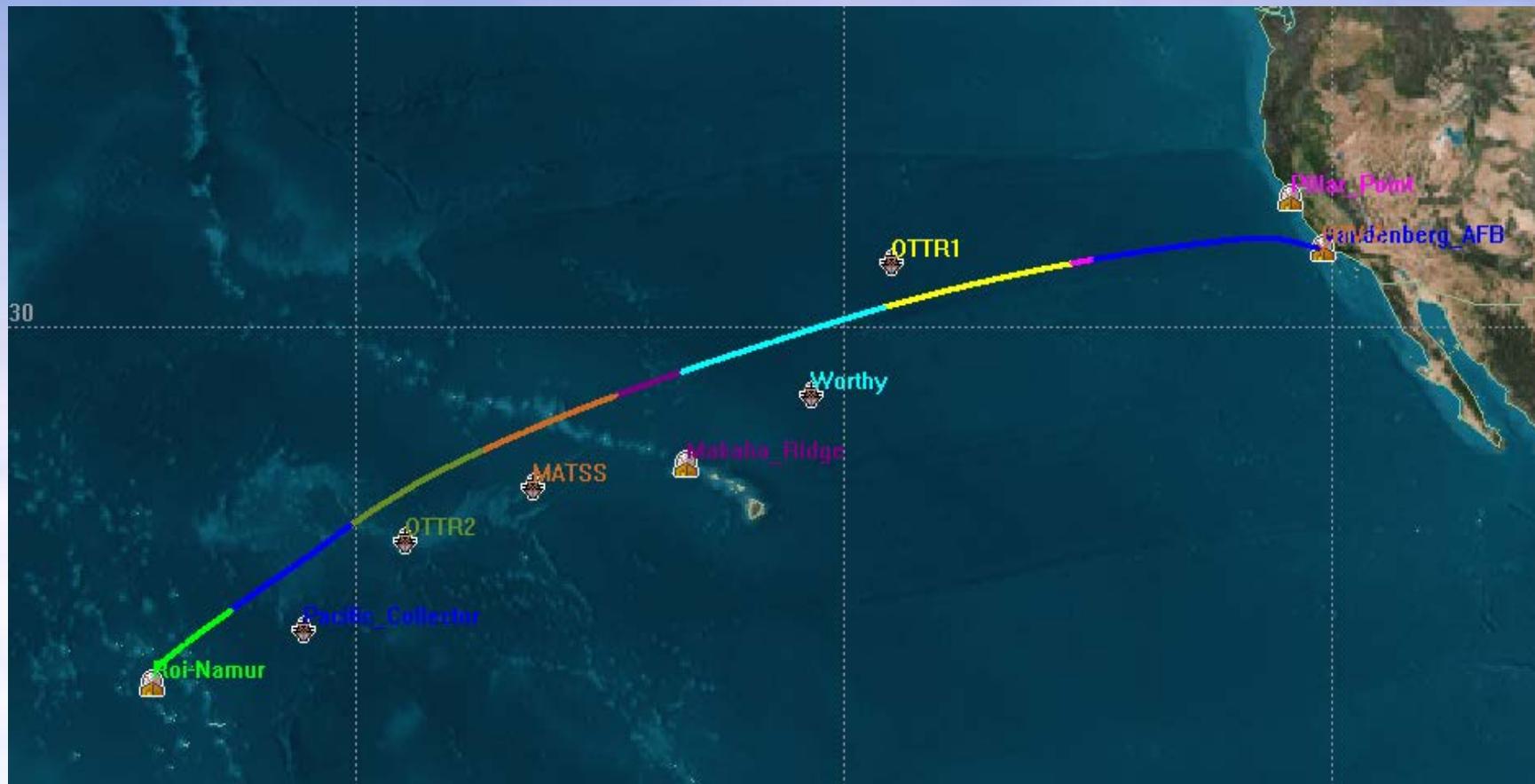
Altitude (kft)	Balloon Uncertainty	HALAS Uncertainty
20	0.47%	0.023%
30	0.49%	0.021%
40	0.63%	0.022%
50	0.71%	0.027%
60	1.01%	0.036%
70	1.30%	0.050%
80	1.87%	0.069%
90	2.86%	0.092%
100	4.57%	0.120%



Aircraft Based

412TW

- Example trajectories requiring TM & FTS coverage





Aircraft Based



High Altitude UAVs

- Provide sufficient coverage
- Can support multiple data transmission/collection systems





Aircraft Based

High Altitude UAVs

- Reduce test costs
- Long duration time-on-station & positioned closer to flight path
- Quantitative
 - Remote sensing/imaging
 - Telemetry data collection/relay
 - TSPI/flight safety
 - Atmospheric characterization
- Critical data for mishap/anomaly investigation; quicker return to flight
- Enable high-G terminal maneuver OT&E over open ocean not allowed at current ranges





Aircraft Based

Data Links

- Link 16 could get around 128kpbs
- Link 16 block 2 should double that (2016-ish)
- TTNT claims it is good up to Mach 8 (Mach 12 with a strong signal) with 10Mbps for 300nm
- TTNT seems to be the best candidate



Space Based



- TDRS - NASA Tracking and Data Relay Satellites
- Inmarsat
- Iridium
- ORBCOMM
- ViaSat



Space Based

- **Advantages**
 - Extended range coverage
 - Cost is competitive
 - Open for business
- **Limitations**
 - Data rates/bandwidth not currently sufficient
 - Transcievers require space, power and cooling
 - Vehicle tracking not easy



Questions?

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